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BREVET D'INVENTION

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Perfectionnements aux régulateurs pour turbines éoliennes.

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On connaît déjà des régulateurs particulièrement convenables pour turbines éoliennes, dont l'organe tachymétrique mesure, non pas la vitesse du groupe lui-même, mais, au contraire, la vitesse du vent, par exemple au moyen d'une petite hélice à pas fixe, entraînée librement par le fluide moteur. Ledit organe tachymétrique commandant le pas de l'hélice principale, on conçoit qu'à chaque vitesse mesurée du vent, on puisse faire correspondre arbitrairement un pas voulu quelconque de l'hélice principale, donc une vitesse définie de l'éolienne, pour une certaine charge.

Ladite éolienne, de type déjà connu, peut donc tourner en fonction de la vitesse du vent avec un décrément de vitesse de rotation arbitrairement choisi, positif, nul ou même négatif. Par ailleurs, en ce qui concerne, pour un vent donné, le décrément de vitesse de rotation en fonction de la charge absorbée par la machine réceptrice, il est bien évident qu'il ne peut être que négatif, et qu'il est déterminé dans ce cas par les caractéristiques naturelles de couple-vitesse de ladite éolienne. Les valeurs courantes de ces caractéristiques sont d'un tel ordre de grandeur que, dans le cas de l'interconnexion par couplage avec un réseau dont le statisme général est inférieur, par exemple, à 5 %, aucun effet pratique de réglage ne pourrait provenir d'un régulateur de ce type déjà connu.

La régulation d'éolienne selon l'invention a pour but essentiellement de permettre aussi bien en régime indépendant qu'en participation dans un réseau d'énergie interconnecté, tantôt d'effectuer l'adaptation aux fluctuations du vent avec le rendement maximum lorsqu'on veut utiliser la totalité de l'énergie récupérable sans considération de réglage, et tantôt à l'occasion de réaliser seul ou de participer au réglage de puissance ou de vitesse de la machine réceptrice en dépit des fluctuations du vent, dans toute la mesure du possible. A titre d'exemple non limitatif, dans le cas particulier d'une éolienne entraînant directement ou indirectement un alternateur synchrone couplé à un réseau interconnecté, l'invention permet notamment de participer au réglage de fréquence avec le statisme voulu, en débit des caractéristiques naturelles de couple-vitesse de l'éolienne, qui peuvent être quelconques dans une certaine mesure.

D'une façon générale, en ce qui concerne l'exploitation des réseaux d'énergie, et comme pour les turbines hydrauliques installées au fil de l'eau, on s'efforcera d'envoyer dans le réseau la totalité de l'énergie récupérable aux éoliennes. Néanmoins, le régulateur selon l'invention pourra rendre des services dans plusieurs cas. A titre d'exemples non limitatifs, il pourra momentanément faciliter le démarrage et l'accrochage au réseau, et remédier automatiquement à certaines défaillances accidentelles de l'interconnexion; ou bien, à titre provisoire, dans les périodes où l'équipement en moyens d'interconnexion ne serait pas encore suffisant ou lorsque les moyens d'accumulation d'énergie seraient déjà saturés; il pourrait également servir à titre définitif dans certaines régions où le vent est la seule énergie naturelle disponible et où n'existent pas de possibilités d'accumulation.

Si le vent était constant, on pourrait évidemment se contenter pour chaque éolienne d'adapter la puissance motrice aux variations de la puissance à absorber par la machine réceptrice. Cette fonction pourrait être assurée par de nombreux régulateurs simples déjà connus, puisqu'il suffirait de mesurer un seul paramètre dépendant de la puissance à absorber, et d'en déduire la commande d'un seul organe de réglage agissant sur la puissance à fournir. Il est à remarquer, d'une part, que de tels régulateurs déjà connus munis d'un seul organe de mesure pourraient donner satisfaction même dans le cas du vent réel variable, tout au moins aux moments où le réglage ne demanderait qu'une faible fraction de la puissance maximum, ce qui

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s'accommode implicitement d'un rendement médiocre. Mais, par contre, aux moments où l'on ne désire pas régler, et où l'on recherche le rendement maximum de l'éolienne, il devient souhaitable de tenir compte de la vitesse instantanée du vent pour satisfaire à la meilleure condition de rendement, qui découle étroitement de l'adaptation de forme ou de vitesse de la turbine ou de son distributeur. On voit qu'il y a en réalité deux problèmes différents dont chacun est justiciable d'un appareil de mesure spécial. En pratique, pour des raisons d'ordre constructif, le régulateur selon l'invention mesurera le plus souvent ces deux paramètres au moyen de deux organes qui peuvent être constamment en service, mais dont les indications ou les commandes ne seront exécutées que selon les besoins du mode d'exploitation du moment.

C'est pourquoi le régulateur selon l'invention est caractérisé essentiellement par l'emploi en combinaison successivement ou simultanément, d'au moins deux organes de mesure distincts, qui jouent le rôle respectivement d'un anémomètre et d'un puissancemètre. Ledit anémomètre étant obligatoirement, mais non exclusivement, en service lors de la marche à rendement ou puissance maximum, et les deux organes étant obligatoirement en service lorsque l'éolienne effectue seule ou participe au réglage de puissance ou de vitesse de la machine réceptrice indépendante, ou du réseau d'énergie interconnecté.

A titre d'exemple non limitatif, dans le cas particulier d'une éolienne entraînant directement un alternateur synchrone couplé à un réseau interconnecté, pour une installation de puissance donnée et le statisme de la centrale étant choisi, la puissance qu'on désire fournir au réseau ne dépend plus que de la fréquence, et le puissancemètre peut donc être remplacé notamment par un tachymètre ou un fréquencemètre. Le régulateur selon l'invention peut utiliser des organes de mesure quelconques. En particulier, l'anémomètre peut être :

Un moulinet ou une hélice auxiliaire entraînant un tachymètre, par exemple du type mécanique centrifuge;

Une girouette à pale mobile ou articulée;

Un tube de Pitot ou un convergent-divergent équipé de prises de pressions appropriées;

Un fil chaud et ses liaisons et accessoires électriques;

Un dispositif utilisant les effets de la force centrifuge de l'air et, d'une façon générale, tous les effets aérodynamiques directs ou secondaires du vent, y compris les efforts ou les déplacements d'une pièce ou partie fixe ou mobile de l'éolienne elle-même ou de ses supports ou équipements annexes.

D'autre part, pour tenir compte des dispositions générales de chaque centrale, les organes ayant trait au régulateur lui-même et à ses liaisons et commandes peuvent être groupés ou répartis en divers endroits au bas des charpentes ou dans la partie fixe ou mobile des organes supports et de la turbine. Il en résulte que le régulateur selon l'invention peut, éventuellement, mettre en œuvre des transmissions à distance et des servo-moteurs de tous systèmes connus tels que mécaniques, hydrauliques, pneumatiques, électriques, magnétiques ou électroniques. La transmission de puissance de l'éolienne équipée d'un régulateur selon l'invention peut être d'un type quelconque, par exemple, soit directe, soit par engrenages ou courroies, soit encore par variateur de vitesse hydraulique, pneumatique ou électrique. Le réglage de puissance de l'éolienne elle-même peut agir indifféremment sur la turbine ou son distributeur de manière à régler la puissance réellement fournie à la transmission. Selon un principe connu, ledit réglage de puissance peut également consister à agir sur un frein hydraulique, par exemple, dissipant le surplus d'énergie qu'on ne veut pas utiliser.

Les figures 1 et 2 représentent, à titre d'exemple indicatif et non limitatif, les courbes de puissance et le schéma de réalisation d'un régulateur selon l'invention, appliqué à une éolienne actionnant une machine réceptrice à vitesse sensiblement constante, et qu'on peut coupler à un réseau de distribution d'énergie classique.

La figure 1 représente en ordonnées la puissance fournie et en abscisses la vitesse du vent. Pour les faibles vitesses du vent de 0 à 1, l'éolienne ne tourne pas ou ne fournit aucune puissance. Pour les vents moyens de 1 à 2, l'éolienne peut travailler à son rendement maximum et l'on sait que la puissance récupérable varie en général sensiblement comme le cube de la vitesse.

Pour les vents forts de 2 à 3, la machine réceptrice peut travailler à sa puissance maximum et l'on doit volontairement en général limiter à cette valeur la puissance fournie. Enfin, pour les tempêtes de 4 à 5, il est nécessaire, selon le cas, de stopper la centrale et de prendre les mesures de sécurité qui s'imposent. Lorsque l'éolienne équipée d'un régulateur selon l'invention doit participer au réglage, à chaque fréquence du réseau correspond une certaine puissance à fournir indépendamment de la vitesse du vent, dans la limite d'énergie disponible définie ci-dessus. Par exemple, pour les fréquences réseau 49, 49.5, 50, 50,5 et 51 périodes par seconde, la puissance fournie peut être celle indiquée par les droites horizontales de mêmes numéros respectifs. Le réglage de statisme correspond à modifier l'intervalle entre lesdites droites. Le réglage charge-vitesse correspond à décaler plus ou moins vers le haut ou vers le bas l'ensemble desdites droites sur la figure 1.

La figure 2 représente le schéma de principe des

organes essentiels d'un régulateur selon l'invention. Ledit schéma comprend certaines organes annexes, à savoir le réglage de statisme et le réglage charge-vitesse, lesdits réglages devant s'entendre au même sens qu'on leur attribue généralement dans l'art des turbines hydrauliques. L'anémomètre est constitué par l'hélice 6 entraînée par le vent, et située, de préférence, immédiatement à l'amont de l'éolienne tout en restant hors de la zone d'interaction. L'hélice 6 entraîne le tachymètre mécanique centrifuge 7 avec ressort de rappel 8 lié à un point fixe, et butée de rotation 9 qui entraîne le déplacement axial de la tige 10.

La came à surface gauche 11 est animée de deux mouvements différents indépendants; à savoir son déplacement axial lié à la tige 10, et son déplacement angulaire lié au manchon claveté coulissant 12 dont la position angulaire est définie par le secteur 13.

Le secteur 13 est commandé en déplacement angulaire par le fil souple inextensible 14 attaché au levier 15 articulé au point fixe 16. Le levier 15 est entraîné par le levier 17 articulé au point fixe 18 et guidé par l'articulation à double coulisse 19 qui permet le réglage de statisme. Le levier 17 est entraîné par la tige 20 dont le déplacement axial est commandé par la butée de rotation 21, liée au tachymètre centrifuge 22 équipé de son ressort de rappel 23. Le ressort 23 est lié au point d'attache réglable 24 qui permet le réglage charge-vitesse. Le tachymètre 22 est entraîné en rotation à vitesse proportionnelle à la fréquence du réseau, au moyen d'une transmission quelconque convenable directe ou à distance, non représentée.

La came à surface gauche 11 entraîne le coulissement du palpeur 25 dans son guidage fixe 26. A chaque position du palpeur 25, correspond une position conjuguée convenable de l'organe principal de commande de puissance non représenté. Ledit organe principal peut être, par exemple, un dispositif à pas variable s'il s'agit d'une hélice, et pour les éoliennes d'une certaine puissance il sera généralement actionné en position par l'intermédiaire d'un relais ou servo-moteur de puissance, connu et non représenté. Pour satisfaire aux meilleures conditions de stabilité, des dispositifs annexes de principes connus tels qu'asservissements temporaires ou accéléromètres pourront être incorporés dans certaines des liaisons cinématiques déjà citées.

Selon les figures 1 et 2, la surface de la came délimitée par les points 27, 28, 29 et 30 est une portion de cylindre circulaire d'axe confondu avec celui de la tige 10; le palpeur 25 ne se trouve dans cette zone que pour les vents faibles de 0 à 1 pour lesquels l'éolienne ne fournit pas de puissance. S'il s'agit, par exemple, d'une hélice à pas variable, ledit pas est nul et l'hélice peut être stoppée. La surface 29, 30, 31 est une portion de surface de révolution d'axe 10; la ligne méridienne de cette surface définit la loi de commande du palpeur 25 pour que le pas de l'hélice s'adapte de façon optimum en fonction de la vitesse de l'anémomètre, ce qui correspond à la portion de courbe caractéristique de 1 à 2 pour laquelle l'éolienne fournit sa puissance maximum variant sensiblement comme le cube de la vitesse du vent. La surface 31, 32, 33, 34 est une portion de cylindre circulaire d'axe 10, pour laquelle l'hélice est en drapeau et peut être stoppée pendant les tempêtes. La surface 29, 31, 32 est une portion de surface gauche qui est établie notamment selon les caractéristiques couple-vitesse de l'hélice, et c'est dans cette seule surface gauche que la position du palpeur 25 se déplace à la fois en fonction des mesures de l'anémomètre 6 et du tachymètre du réseau 22, ce qui permet la régulation de puissance du réseau selon les droites caractéristiques telles que 49 à 51.

Par contre, lorsque le réglage charge-vitesse 24 est à fond de course dans le sens compression du ressort 23, quelle que soit la fréquence du réseau, le tachymètre 22 est en butée et le palpeur 25 touche la came le long de la ligne 27, 30, 31, 34 selon la vitesse du vent, ce qui correspond à la marche normale de l'éolienne à puissance maximum récupérable, sans considération de réglage du réseau. En pratique, pour diverses raisons, notamment d'ordre constructif ou fonctionnel, les diverses surfaces de la came pourront être raccordées par des congés convenables.

L'invention comprend de nombreuses variantes de réalisation, et notamment, dans certains cas particuliers, il est possible pratiquement de remplacer la came gauche à trois dimensions par deux cames planes à deux dimensions.

RÉSUMÉ

Dispositif régulateur d'éolienne caractérisé par l'emploi en combinaison d'au moins deux organes de mesure distincts, jouant le rôle respectivement d'un anémomètre et d'un puissancemètre. Lesdits organes de mesure sont utilisés simultanément pour le réglage de l'éolienne lorsque celle-ci participe au réglage de puissance ou de vitesse de la machine entraînée. Par contre, lorsque l'éolienne ne participe pas au réglage, l'anémomètre peut n'être que seul en service.

Société dite : ÉTABLISSEMENTS NEYRPIC
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Fig. 1

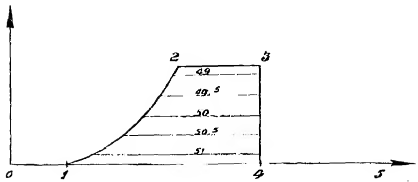
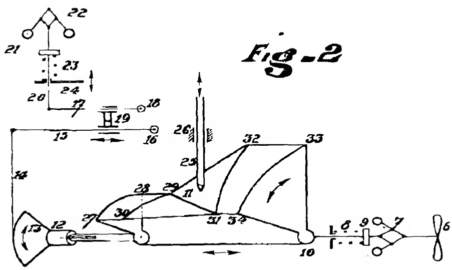


Fig. 2



Role and objectives of control for wind turbines

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Abstract: Variable pitch is used in many wind turbines to regulate power generation. The choice of control objectives is broadly examined together with the influence of the controller on the dynamics of the wind turbine.

1 Introduction

It is the purpose of the paper to investigate and clarify the role of the control system of a wind turbine. A complete review of the control and modelling of wind turbines has been given by Leithead [1].

There are two basic configurations of wind turbines, the horizontal axis wind turbine depicted in Fig. 1*a* and the vertical axis wind turbine depicted in Fig. 1*b*. Control issues are relevant only to the former, and the wind turbines discussed in this paper are of that type. The major components of the turbine are the tower, rotor (the blades and hub) and power train (the drive train and power generation unit). The drive train consists of the low-speed shaft, gearbox and coupling, if any, and high-speed shaft as shown in Fig 2. The wind turbine configuration is assumed to conform to the following specification

(i) horizontal axis
(ii) grid connected
(iii) medium/large scale
(iv) variable pitch capability
(v) all blades acting in unison
(vi) generated power measurement.

There are no further restrictions. The turbine may be constant speed with or without compliance adding devices in the drive train or variable speed with all possible speed ranges. It is assumed that the variable pitch capability is employed in a regulating fashion, with all blades acting in unison, and the operational usage which best exploits it (and cost/efficiency implications) is investigated.

To have each blade acting independently requires independent instrumentation and actuation for each blade plus co-ordination of regulation at a higher level. The extra cost involved is generally assessed by the industry to outweigh any benefits [2, 3]. There is in principle, however, no difficulty in providing independent control of each blade, and this might be incorporated in

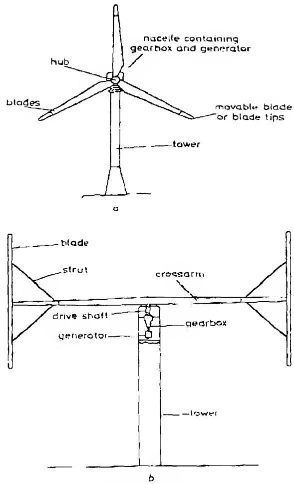

Fig. 1 *Wind turbine configurations*
a Horizontal axis wind turbine
b Vertical axis wind turbine

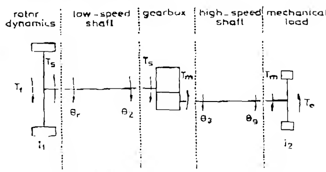

Fig. 2 *Schematic form of physical model for drive train*

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the next generation of control designs. Comparisons with other methods of regulating wind turbines, such as stall regulation, are not made.

2 Review of pitch regulation

The reasons which led to the introduction of variable pitch capability on medium and large scale wind turbines were to assist with start up and shut down operation, to provide overspeed protection and to limit the load on the wind turbine.

The turbine is normally operated between a lower and an upper limit of windspeed, typically 5 m/s to 25 m/s. When the windspeed drops too low to generate worthwhile quantities of power the turbine is stopped to reduce wear. When the windspeed rises too high it is again stopped since it would be uneconomic to construct the turbine to be robust enough to operate in all windspeeds. The wind turbine must be capable of being started and run up to speed in a safe and controlled manner. The aerodynamic characteristics of some turbines are such that they are not self starting. The required starting torque may be provided by motoring or by changing the pitch angle of the blades. In either case, once started, the rotor acceleration rates and speed must be controlled prior to synchronisation with the grid. Shut down must be similarly controlled by feathering the blades on variable pitch machines: mechanical brakes only being used during the later stages.

In normal operation, medium to large scale wind turbines are connected to a large grid, a consequence of which is to lock the rotational speed of the generator to the frequency of the grid. When the generator is directly driven by the rotor, the grid acts like an infinite load. In the event of system failure the load rapidly decreases to zero causing the turbine rotor to accelerate quickly. In emergency conditions overspeed protection must be provided by rapid braking of the turbine. Industrial practice has tended not to favour a reliance solely on mechanical brakes, since the demands on them would be very great because of the large inertia of the rotor and the large driving torque. The general opinion is that some aerodynamic assistance is preferred.

As the windspeed increases, the energy available for capture increases as roughly the cube of the windspeed. The high wind speeds are not encountered frequently enough to make it economic to extract the total energy available. A correspondingly high rating is required for the power train, which during normal windspeed would operate at a fraction of its capability in an inefficient manner, and the cost of the over-engineering involved is prohibitive. The alternative of aerodynamic power limiting is preferred. The normal method is to change the rotor and aerodynamic characteristics, either passively by stall regulation or actively by pitch regulation. At a predetermined windspeed (rated windspeed) the power input to the wind turbine will have reached the limit for continuous operation (rated power). When the windspeed exceeds this level the excess power in the wind must be discarded by the rotor to prevent the turbine overloading. The power is maintained at its rated value until a maximum windspeed is reached when the turbine is shut down (cut-out windspeed). A typical power curve is shown in Fig. 3. On varying the pitch of the blade, the power derived from the wind is reduced by either partially feathering the blades or rotating the pitch in the opposite direction to induce stall.

Power limiting does not, however, induce smooth power, and in recent years it has been recognised by the industry that varying the pitch of the blades may be exploited to smooth the power. The windspeed can be

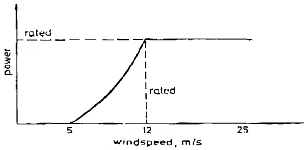

Fig. 3 *Typical power curve*

interpreted as consisting of two components. A slowly varying mean windspeed of, say, hourly averages plus a rapidly varying turbulent component. The former is usually modelled as a Rayleigh distribution.

$$p_R(V) = aVe^{-1/2aV^2} \tag{1}$$

where V is the hourly windspeed average and a is related to the very long time scale (of the order of years) mean windspeed. The latter is modelled by a normal distribution with mean zero and standard deviation proportional to the concurrent value of the average windspeed. The constant of proportionality is termed the turbulence intensity. The spectrum for the turbulent component is the Von Karman spectrum, which is the power spectrum as measured by a small anemometer.

$$S(\omega) = \frac{0.475\sigma^2 L/V}{[1 + (\omega L/V)^2]^{5/6}} \tag{2}$$

where σ is the turbulence intensity and L is the turbulence length scale. The turbulence together with wind shear and tower shadow induces rapidly fluctuating loads on the wind turbine which consequently appear as large rapid fluctuations in power.

Smooth output power has a traditional appeal to the electricity supply industry as it has no experience of such rapidly fluctuating power sources. The more refined commercial turbines strive to obtain good power quality. (In this paper, the term 'good power quality' refers to when the extent of rapid fluctuations in the generated power is small). Improvement in power quality can be achieved by continuously monitoring the wind turbine and altering the pitch angle of the blades accordingly. A control system, which incorporates the ability to vary pitch in an active feedback control, is required to be added to the turbine.

An alternative is to design a fixed pitch rotor with blades that stall at the rated windspeed. At higher windspeed stalled rotors produce smooth power through their insensitivity to fluctuations in windspeed, but the wind turbine structures experience greater mean thrust loads, [2 and 3]. A stalling rotor is self-regulating providing power limiting and good power quality without the need for a control system. Aerodynamic assistance for start up, shut down and overspeed protection requires further consideration. Stall regulation is still at the development stage, with the design of the blades not totally understood, and will not immediately supersede pitch regulation, particularly for large machines.

However, power fluctuations are not the most important consequence of the variation of loads. This variable load environment contributes greatly to the fatigue of the turbine components. To guarantee an acceptable fatigue life the components are specified to withstand loads greater than those required by the nominal rating of the turbine. Variations in loads cannot be completely eliminated but reducing their magnitude is desirable. The load capacity of the components can be set closer to the turbine rating without sacrificing fatigue life; increased power production is possible, or, equivalently, lower specifications for components.

We consider the alleviation of fatigue damage to be one of the primary uses of pitch regulation of wind turbines.

3 Review of control benefits

Consider a plant, i.e. a machine which responds dynamically to some external influence, Fig. 4*a*. The basic problem is to make the output follow the input. The solution is to employ a feedback loop. The output from the plant is measured and compared to the desired response with the error used to adjust the plant through a controller. This is the closed-loop system, Fig. 4*b*, as distinct from the system with the controller present but no feedback loop which is the open-loop system, Fig. 4*c*. It is the dynamic response of the closed-loop system (not the open-loop system) which determines system performance. As well as causing the output to follow the input the controller can achieve several things.

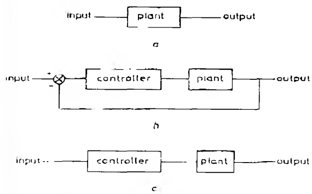

Fig. 4 *Controlled and uncontrolled systems*
a Uncontrolled system
b Closed-loop system
c Open-loop system

3.1 *The controller determines the overall dynamics*

Consider the following grossly simplified model of a wind turbine. The dynamics are represented by a second order spring, mass and damper system.

$$I\ddot{\phi} + B\dot{\phi} + K\phi = T_A \tag{3}$$

where I, B and K are the aggregate wind turbine inertia, damping and stiffness, $\ddot{\phi}$, $\dot{\phi}$ and ϕ are the rotor shaft acceleration, velocity and position. T_A is the rotor aerodynamic torque.

Control action is introduced by feedback from the system output, altering the input driving torque. A simple proportional plus integral control acting on shaft speed may be used as an illustration. The wind turbine model is modified to

$$I\ddot{\phi} + B\dot{\phi} + K\phi = T_A - T_f \tag{4}$$

where, the control action

$$T_F = k_1\phi + k_2\dot{\phi} \tag{5}$$

k_1 is the control integral gain on shaft speed and k_2 is the control proportional gain. Substituting eqn. 5 into eqn. 4 gives the amended dynamics

$$I\ddot{\phi} + (B + k_2)\dot{\phi} + (K + k_1)\phi = T_A \tag{6}$$

The damping factor of the system appears to have been modified to $(B + k_2)$ and the stiffness to $(K + k_1)$. Of course, they have not physically been altered, but the dynamics and all the forces experienced by the system behave as if the system had been altered as indicated.

If the control action of eqn. 5 can be introduced with no penalty, then the system performance could be altered to any desired form. Unfortunately, this is not possible. The first penalty is that the greater the alteration of the system then the harder the control action has to work. The second penalty arises since the measurement on which the control acts is inevitably corrupted by noise. The noise is fed into the system through the controller and adversely affects its performance. Again, the greater the alteration of the system the greater the penalty. When choosing a control design the tradeoff must be carefully assessed.

In general, the addition of damping is easier to achieve than the addition of stiffness. The use of feedback control can be used as an alternative to mechanical methods of increasing damping in the drive train.

3.2 *The controller shapes the output spectrum*

Consider the system in Fig. 5*a* where the dynamics are represented by $G(s)$, the transfer function of the system. If the system is linear and time-invariant then the dynamics are characterised by the response of the system to an impulse as indicated in Fig. 5*b*. $G(s)$ is the Laplace Transform of the impulse response function. To obtain spectral information about a system the frequency response function $K(\omega)$, which is 2π times the Fourier transform of the impulse response function, is required. For stable causal systems

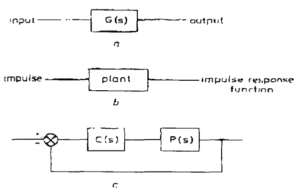

Fig. 5 *System transfer and response functions*
a Transfer function representation of open-loop system
b Impulse response of system
c Transfer function representation of closed-loop system

$$K(\omega) = G(j\omega) \tag{7}$$

Hence, for the system with transfer function $G(s)$

$$\text{spectrum of output} = |G(j\omega)|^2 \times \text{spectrum of input}$$

When the system is the closed-loop system, Fig. 5*c*, with $P(s)$ the transfer function of the plant and $C(s)$ the trans-

fer function of the controller

$$G(s) = \frac{C(s)P(s)}{1 + C(s)P(s)} \tag{8}$$

and

$$\text{spectrum of output} = \left| \frac{C(j\omega)P(j\omega)}{1 + C(j\omega)P(j\omega)} \right|^2$$

× spectrum of input

Thus the output spectrum is shaped by the controller.

3.3 The controller reduces the effect of disturbances

The plant may also be subject to unwanted disturbances. The influence of these on the output of the system is reduced by the controller, i.e. it enhances the disturbance rejection properties of the system. The plant model is as indicated in Fig. 6, with P' representing any dynamic shaping of the disturbance by the plant. What is considered as an input and what a disturbance is identified by its position in the feedback loop relative to the controller.

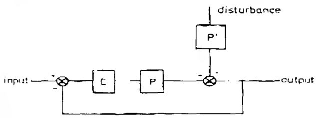

Fig. 6 *Model of plant with disturbances*

In control system design and analysis, models of the dynamics are required. It is not necessary for them to be complex detailed models, in fact the simpler the better. However, it must be ensured that all significant parts of the dynamics are represented [4].

4 C ntrol interpretation of a wind turbine

There are strong pressures to make wind turbines as economical as possible by optimising the technology and reducing over-engineering to a minimum. This requires a working life of 15 to 25 years with a minimum of maintenance. Also, to minimise visual impact, offshore siting is attractive but to become feasible requires bigger machines at reduced cost since additional costs of construction and delivering the power to land must be borne. Hence, the drive is towards lighter, softer and more dynamically active wind turbines. At first sight, the control system does not appear to be involved and the dynamics appear simple. However, the set of interlinked dynamics which can become active at low frequency includes aerodynamics, blade dynamics, drive train dynamics, tower dynamics, generator dynamics and control system dynamics as in Fig. 7. To illustrate just one of these, the Campbell diagram of Fig. 8, [5], depicts

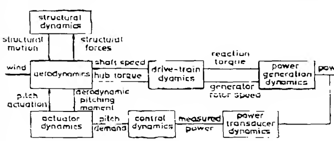

Fig. 7 *Wind turbine dynamics*

the tower and blade resonances for a typical three bladed machine. One feature of the dynamics is that they have a tendency to be lightly damped since the purpose of a wind turbine is to generate power as efficiently as possible. If it were not so the energy would be dissipated wastefully.

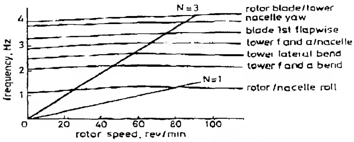

Fig. 8 *Campbell diagram of structural resonances*

Since control requires minimalist models, Fig. 7 is simplified to Fig. 9. Structural dynamics are not ignored but are included by

(i) inclusion of edgewise blade mode(s) in drive-train dynamics

(ii) correlating moments and forces to hub torque, e.g. correlating blade flapwise bending moments at root to hub torque

(iii) noting position of resonances at low frequency and if necessary suppressing their excitation.

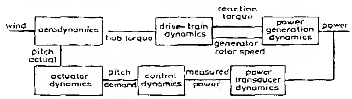

Fig. 9 *Reduced wind turbine dynamics*

The drive-train dynamics are shown in Fig. 10. Not all the elements are significant for all configurations of wind turbines. It is the distribution of compliance along the drive train and generator that determines which is important.

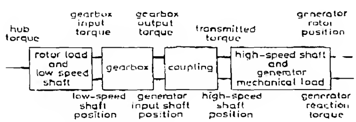

Fig. 10 *Drive-train dynamics*

The part played by the control system in shaping the dynamics must be identified so that the role of the control system be defined. Once that has been resolved the criterion by which control is judged may be formulated and the extent to which it assists in optimising the technology and reducing the over-engineering to a minimum may be determined.

5 Interaction of the wind turbine with the wind

It is important to understand the interaction of the wind turbine with the wind. The wind is the input which drives the wind turbine and the available power and turbulence

are characterised by its spectral content. The resulting torques and moments, to which the wind turbine structure and power train are subject, are modified by the dynamics of the turbine and the control systems. The analysis of Madsen and Frandsen [6] is extended to identify the precise manner in which this occurs. The interaction is examined in some detail here.

The windspeed varies stochastically in both a temporal and spatial manner to form a three-dimensional wind field. It may be pictured as a tube throughout which the windspeed varies not only longitudinally but over the cross-section of the tube at any point. The longitudinal axis of the tube represents time and the wind turbine moves along the tube experiencing, at any one time, a cross-section of the tube. Thus, the wind turbine does not experience a single windspeed but a windspeed which varies over the disc swept by the rotor. The direction of the wind also varies in time and over the disc. Hence, the spectral representation of the windfield must be multidimensional to include the variations, both in magnitude and direction, of windspeed over the swept disc.

The windfield spectra, as seen at a point on the rotor, are shaped by the motion of the blades. First, the rotation of the rotor, as indicated in Fig. 11, changes the

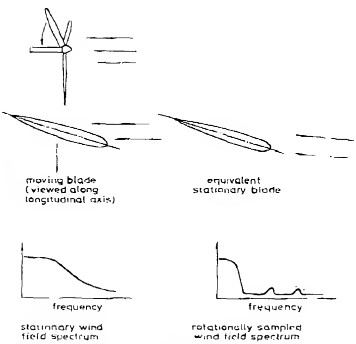

Fig. 11 *Effect of rotation of blades on wind field spectrum*

direction of the windspeed relative to the blades and accordingly modifies the spectra at all frequencies. In addition, it increases the high frequency parts of the spectra at multiples of Ω, the rotor angular velocity. This concentration in energy is caused by each blade in turn sweeping through variations in windspeed over the swept disc. The variation in windspeed includes tower shadow which is the reduction in windspeed in front of the tower, wind sheer which is the increase in windspeed with height as the boundary effects decrease and localised wind gusts. Secondly, the pitching of the blades about their longitudinal axis, as indicated in Fig. 12, again shapes the spectra by changing the relative windspeed. Thus in a fundamental way the control system, by changing pitch angle, influences all the wind induced forces and torques which drive the wind turbine dynamics.

In accordance with the response of the system to the fluctuating loads, the feedback control changes the blade pitch to cause a change in the induced torques and moments. The effect of these changes in pitch can be

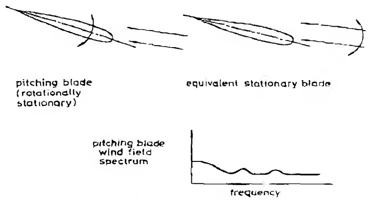

Fig. 12 *Effect of pitching blades on wind field spectrum*

interpreted as inducing equivalent changes in windspeed which leave the windfield spectra as experienced by a blade unaltered. Rather than changing pitch angle the influence of the control system may be depicted as in Fig. 13. $\boldsymbol{P}$ incorporates the aerodynamics which converts the

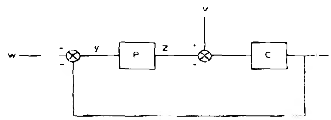

Fig. 13 *Modification of windspeed induced dynamics*

windspeed inputs into driving torques and forces, the structural dynamics, the power train dynamics and measurement transducer dynamics. $\boldsymbol{C}$ incorporates the control system dynamics, the pitch actuator dynamics and the dynamics required to convert changes in pitch angle to equivalent changes in windspeed. $\boldsymbol{W}$ are windspeed inputs, y are the equivalent windspeed inputs including the control action, z is the measured output of the turbine (usually power) and v is the measurement noise. Fig. 13 is an exact representation of the wind turbine. $\boldsymbol{P}$ and $\boldsymbol{C}$ are nonlinear operators which model the complete nonlinear dynamics of the system. Since it is the influence of the input y on the plant $\boldsymbol{P}$ that is of interest, an equivalent representation is as indicated in Fig 14*a*.

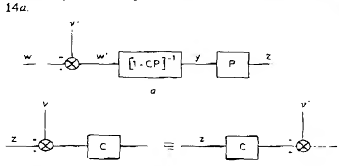

Fig. 14 *Equivalent representations*
a Equivalent representation of Fig. 13
b Equivalent measurement noise representations

The measurement noise, v', in Fig. 14*a* is related to v as in Fig. 14*b*. Assuming the spectral density function of v is fixed, the spectral density function of v' varies with the value of z since C is nonlinear. In characterising measurement noise the details of the shape of the spectral density function is normally not particularly well known. However, the important property to be represented by v is the presence at some specified level of significant components over a broad frequency range including high frequencies. Given the inexact nature of v and assuming the control system is well designed so that the measurement noise does not compromise its performance over part of its operating envelope, it is possible, except in unusual circumstances, to determine an alternative representation of the measurement noise as in Fig. 14*b*.

It is the equivalent windspeed input $y = [1 + CP]^{-1}w'$ which is the source of the transient loads. The spectral density functions of the windfield over the rotor are replaced by equivalent spectral density functions, and the feedback control action has no further consequence (i.e. the wind turbine is essentially treated as fixed pitch). If all the structural and power-train dynamics were taken into account when determining the equivalent windfield spectral density functions over the rotor disc then the response of the wind turbine, with fixed pitch, is indistinguishable from the active pitch controlled wind turbine, i.e. all the forces, torques and moments over a time interval, for the representations are indistinguishable. The equivalent spectral density functions can be used to generate input forces to drive the structural dynamics and assess fatigue damage to the blades and tower. It can also be used to generate torques to drive the power train and assess the fatigue damage to components in the power train such as the gearbox and generator. As the design of the control system varies, so does the equivalent spectral density function and so do the loads on the system. This is clearly seen in the development of the control system for the MOD-2 wind turbine [7].

The progression of the transient loads is traced through P in Fig. 15. P_1 incorporates all the power train

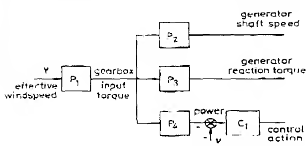

Fig. 15 *Progression of transient loads along drive train*

dynamics which relate the gearbox input torque to the equivalent windspeed inputs; P_2 incorporates the dynamics which relate the generator shaft speed to the gearbox torque; P_3 incorporates the dynamics which relate the generator reaction torque to the gearbox torque; P_4 incorporates the dynamics which relate the generator power to the gearbox torque; C_1 incorporates the dynamics which relate the control action to the generated power. As before, Fig. 15 is an exact representation with P_1, P_2, P_3, P_4 and C_1 nonlinear operators. Their relationship to the loads on the wind turbine components is depicted in Fig. 16. The effect of the control system on the structural loads may be assessed from the equivalent windspeed, the effect on the gearbox from the gearbox input torque, the effect on the generator from the gearbox speed and reaction torque, the effect on power smoothing from the power output and the control action cost from the control action output.

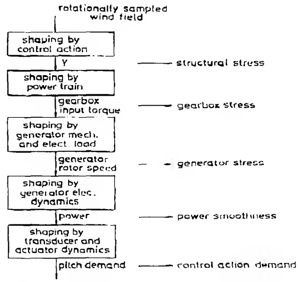

Fig. 16 *Relation of transient loads to turbine stress*

6 Effective windspeed spectral density function

Having established the extent of the influence of the control system on the wind turbine, the representation of the system is simplified. To determine the wind input which drives any particular component of the aerodynamics or structural dynamics, the spectral contribution of a small element is obtained and integrated over the relevant part of the turbine. Of particular interest here is the rotor torque which drives the turbine rotor, the spectrum for the moment, perpendicular to the blade in the plane of the rotor, induced at a point by the windfield is determined and integrated over each blade to obtain the total torque. The result is a single spectrum which can be represented as being due to an effective windspeed spectrum rather than the windfield spectra, i.e. the spectrum for an average windspeed constant over the rotor disc that induces the same rotor torque spectrum.

For windspeed at a point the appropriate spectral density function is the Von Karman spectrum, Fig. 17*a*. However, as previously indicated, the turbine blades sweep through the three dimensional windfield which modifies it, Fig. 17*b*, as in Connell and George [8] and Kristensen and Frandsen [9], who have shown that the spectrum is basically Von Karman at low frequencies with power transferred from the midfrequency range to peaks at multiples of the blade passing frequency. The peaks contain both a stochastic contribution due to the wind turbulence and a deterministic cyclic contribution due to tower shadow, wind shear etc. The latter are not infinitely narrow since they are broadened by the fluctuations in shaft speed. Thus the windspeed spectrum is modelled by shaping the Von Karman spectrum by an appropriate transfer function. This windspeed spectrum for the windspeed input w, is designated $S_w(\omega)$.

The measurement used as input to the controller is inevitably corrupted by noise, v. The noise influences the control action and results in errors in positioning the blades, which are experienced by the wind turbine as changes in the torques and moments. The measurement

noise and wind are assumed to be uncorrelated and from Fig. 14*a* the spectral density function for the turbulent

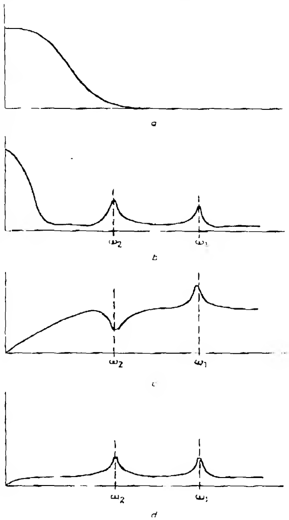

Fig. 17 *Frequency spectra*
a Von Karman spectrum
b Rotationally sampled spectrum
c $|1 + CP|^{-2}$
d $|H|^2$

wind as experienced by the blades is amended to

$$S_{w'}(\omega) = S_w(\omega) + S_{v'}(\omega) \tag{9}$$

The wind spectrum experienced by the blades is not only modified by the rotational motion of the blades but is also modified by the axial motion of the blades, the bandwidth of which can easily include most of the significant frequency range of $S_{w'}(\omega)$. To obtain greater insight, the wind turbine system is linearised about some operating point. The operators P, C, P_1, P_2, P_3, P_4 and C_1 become the transfer functions P, C, P_1, P_2, P_3, P_4 and C_1. The measurement noises are related by

$$v' = Cv \tag{10}$$

and their spectral density functions by

$$S_{v'}(\omega) = |C|^2 S_v(\omega) \tag{11}$$

The combined windspeed and measurement noise spectrum becomes

$$S_{w'}(\omega) = S_w(\omega) + |C|^2 S_v(\omega) \tag{12}$$

The limitation placed on the control by the presence of measurement noise as mentioned in Section 3 can be assessed from eqn. 11 or 12. The noise is usually assumed to be white noise when $S_v(\omega)$ becomes constant. The contribution of the noise to the input spectrum increases with $|C|$, and hence with the control gains.

By changing the pitch angle of the blades, the dynamics of the plant and controller modify the input to the wind turbine. From the previous discussion, it can be interpreted as being due to a turbulent wind, and from Fig. 18*b* the effective spectral density function is

$$S_\beta(\omega) = \frac{1}{|1 + CP|^2} S_{w'}(\omega) \tag{13}$$

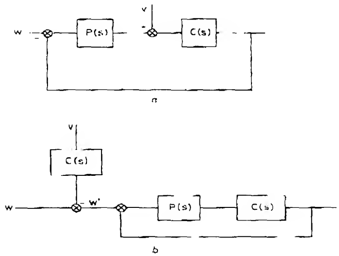

Fig. 18 *Dynamics models*
a Linearised model of wind turbine dynamics
b Equivalent representation of dynamics

In Madsen and Frandsen [6] it was essentially assumed that

$$CP = (\alpha f_0)/(j\omega) \tag{14}$$

i.e. the power train was assumed to have no dynamics and the control was simple integral action.

7 Influence of control systems on tower and blades

To estimate the loads on the blades and tower, the structural dynamics must be driven by a wind input modified by the operator $[1 + CP]^{-1}$. However, to assess the influence of the control action on a particular blade or combined blade and tower mode of the structural dynamics, only the frequency response function H, coupling the input to that mode need be known. A possible shaping function, $|1 + CP|^{-2}$, is shown in Fig. 17*c* and $|H(\omega)|^2$ in Fig. 17*d*. A comparative estimate of the structural loads can be determined directly from the effective windspeed spectrum. The spectral density function, $S_S(\omega)$ for the resulting excitation of the mode is

$$S_s(\omega) = \frac{|H|^2}{|1 + CP|^2} S_{w'}(\omega) \tag{15}$$

The contributions of all the significant structural mo[des] need to be included.

To reduce structural loads the shaping function, $|1 + CP|^{-2}$, should reduce the magnitude of the input spectrum at the structural resonances since it is the power in the spectral density function near these frequencies which will excite the structural modes. In Fig. 17, at frequency ω_1, a peak in $S_{w'}(\omega)$ coincides with peaks in $|1 + CP|^{-2}$ and $|H|^2$, which is more damaging to the structure than the peak in $S_{w'}(\omega)$ at ω_2, which coincides with a peak in $|H|^2$ but a trough in $|1 + CP|^{-2}$. (These are extreme cases, since normally the structural modes would not coincide with multiples of the rotor speed). In addition the high frequency components of the spectral density function are relatively more damaging than the low frequency, [10]. For a given wind turbine, $S_{w'}(\omega)$ and $|H|^2$ are known. The relative merits of alternative control actions are judged by comparing the shape of $|1 + CP|^{-2}$ to the shapes of $S_{w'}(\omega)$ and $|H|^2$. Although it is not entirely clear from the information given, it would appear from Gordon *et al.* [7] that the design of the control system for the MOD-2 wind turbine was adjusted, over eighteen months on an *ad hoc* basis, until the shaping function $|1 + CP|^{-2}$ counteracted the excitation of structural modes.

To simplify the preceding analysis, the spatial variation, over the disc of the windfield, and hence of the loads has been neglected. The variations in the aerodynamic coefficients over the disc are accounted for in the operator $[1 + CP]^{-1}$ but are not in the scaling factors $|1 + CP|^{-2}$ in eqn. 13. Nevertheless, for the purpose of comparing different control actions $|1 + CP|^{-2}$ is an adequate approximation. The profile of the windfield also determines the extent to which the structural modes are excited and the extent of the aerodynamic damping [2, 11]. Without individual blade control, to cater for these alterations in the structural dynamics is not within the capabilities of the controller. However, to assess different control actions the exact details of $|H|^2$ need not be known. Only the frequencies of the modes and their approximate width are required together with a ranking in terms of importance. If need be, a weighting function $|H_1|^2$, can be formulated which includes this information. In addition, the structural modes themselves, when excited, modify the effective input spectral density function. However, only in extreme cases would the effective windspeed be noticably affected since the speed of motion of the structure is small compared to fluctuations in the windspeed. It might then affect the estimation of the load but would not affect the comparison of control actions, particularly for controllers that do not enhance these modes.

8 Influence of control systems on power train components

The manner in which the control action interacts with the wind turbine has been determined. The modified input windspeed and a means of relative load assessment for the blades and tower have been obtained. The power train is subject to the same input and the implications for it remains to be similarly assessed. The propagation of the loads is shown in Fig. 15.

Gearbox fatigue is caused by stressing of the gearbox teeth in response to torque overloads. For an input torque in excess of the gearbox rating, the fatigue damage increases as the extent to which the rating is exceeded increases and, also, increases as the length of time the overload persists increases [3]. Hence, a useful indicator of gearbox fatigue above rated windspeed is the variance of the input torque to the gearbox, i.e. the area under the spectral density function $S_{GB}(\omega)$ of the input torque where

$$S_{GB}(\omega) = |P_1|^2 S_E(\omega) \tag{16}$$

Generator fatigue is caused by thermal stressing of the generator windings. It increases as the generator rotor speed increases above its rated speed and, also, increases as the time spent above rated rotor speed increases [3]. Hence, a useful indicator of generator fatigue above rated windspeed is the variance of the high-speed shaft speed, the area under the spectral density function, $S_G(\omega)$ of the high-speed shaft speed where

$$S_G(\omega) = |P_2 P_1|^2 S_E(\omega) \tag{17}$$

The gearbox couples to the tower through the reaction to the forces on it. These forces act transversely. Their spectral density function is proportional to the spectral density function, $S_{GB}(\omega)$, of the gearbox. The structural load implications are assessed by the same means as for the direct structural loads in Section 7. Hence, only the frequencies of the transverse tower modes and their approximate width are required together with a ranking in order of importance. Again, a weighting function, $|H_2|^2$, can be formulated which contains this information.

Measures have been obtained for assessing the manner in which the control action modifies the various stresses to which the wind turbine is subject. (These are not meant to be definitive but simple and easy to use in a control context). If the control action moderates the stresses then the power quality also improves. The variance of the power generated is a convenient measure of the power quality, i.e. the area under the spectral density function $S_P(\omega)$ for the power where

$$S_P(\omega) = |P_4 P_1|^2 S_E(\omega) \tag{18}$$

Finally, the magnitude of the control action cannot be allowed to become excessive. A suitable measure for the magnitude of the control action is its variance, i.e. the area under the spectral density function of the control demand $S_C(\omega)$. For wind turbines, a typical limitation on the control action is the rotational velocity at which the pitch of the blades can be altered or the rate of change of the pitch velocity, [2, 3]. Also the control action should not have an excessively high frequency component. A shaping function, $|H_3|^2$, can be combined with $S_C(\omega)$ to restrict both to these factors. A typical choice might be

$$|H_3|^2 = \omega^2 \tag{19}$$

Normally, the control action is driven by a power measurement, particularly for constant speed wind turbines, when the control demand is, from Fig. 15, $C_1(v + P_4 P_1 y)$ and

$$S_C(\omega) = |C_1|^2 |1 + CP|^{-2}(|P_1 P_4|^2 S_w(\omega) + S_v(\omega)) \tag{20}$$

which for low levels of noise reduces to

$$S_C(\omega) = |C_1 P_4 P_1|^2 S_E(\omega) \tag{21}$$

9 General cost function for the control system

To assess a control system for a wind turbine each of the spectral items of Sections 7 and 8 must be considered. A single unified measure which can be used for optimised

control design purposes has the following structure

Structural loads	$J = \int_{-\infty}^{\infty} \{a_1^2 \mid H_1 \mid^2 S_E(\omega)$
Gearbox loads	$+ a_2^2 S_{GB}(\omega)$
Generator loads	$+ a_3^2 S_G(\omega)$
Transverse tower loads	$a_4^2 \mid H_2 \mid^2 S_{GB}(\omega)$
Power smoothness	$+ a_5^2 S_P(\omega)$
Control cost	$+ a_6^2 \mid H_3 \mid^2 S_C(\omega)\} \, d\omega$ (22)

The control system is designed to minimise, in some sense, the cost function, J. It is simply a weighted average of the power associated with each of the indicators of performance previously discussed.

The various spectra in the cost function (22) are

$$S_{GB}(\omega) = \mid P_1 \mid^2 S_E(\omega)$$
$$S_G(\omega) = \mid P_2 P_1 \mid^2 S_E(\omega)$$
$$S_P(\omega) = \mid P_4 P_1 \mid^2 S_E(\omega)$$
$$S_C(\omega) = \mid C_1 \mid^2 \mid 1 + CP \mid^{-2}(\mid P_1 P_4 \mid^2 S_w(\omega) + S_v(\omega)) \quad (23)$$

The relative importance of each of the terms reflected in the value of the scale factors, a_i, is strongly dependent on the turbine configuration and will inevitably involve tradeoffs. Although J seems complex many of the terms will be negligible and may be left out when used to assess a particular wind turbine. Moreover, a complex cost function need not necessarily give rise to a complex control system design, but allows a more thorough evaluation.

10 Control and structural fatigue

Although the influence of the control system on the structural loads has been discussed, the relevance for structural fatigue remains to be clarified. The structural loads can be considered to be composed of three components. The first contribution to the total is the mean loads over the rotor disc which would arise if the blades are controlled perfectly and the pitch angle is appropriately set for the mean windspeed experienced by the wind turbine at any given time, i.e. the design loads. The second is the mean loads over the rotor disc which arise from the control being imperfect and the pitch angle not being appropriately set, i.e. the off design loads. The third is the loads due to the variation of the windspeed over the rotor disc which occur at multiples of the rotor angular velocity Ω, i.e. the cyclic loads.

In the main above rated windspeed, the design loads are less for a pitch regulated than for a stall regulated machine but the cyclic loads are larger. Of course, the off design loads are not applicable to a stall regulated wind turbine. However, it is not our purpose to compare pitch regulation to stall regulation.

The fatigue damage is assessed by counting the number of occurrences of cycles with each possible amplitude in the total loads. The bulk of the damage is caused by the cycles with greatest amplitude which occur at low frequency [2, 3]. It is the superposition of the three components of the structural loads which generate these low frequency cycles. Even though it is not possible to remove the low frequency cycles, reducing the higher frequency components of the loads reduces the fatigue damage caused by them by reducing their amplitude.

The control system affects the structural fatigue by determining the extent of the off-design loads. One of the objectives of the control system should be to reduce these. In addition, if the control system of a constant speed wind turbine (Section 11), performs poorly in regulating drive train loads, particularly as the mean windspeed increases, then the power rating of the wind turbine may need to be reduced with rising windspeed. A consequence is an increase in fatigue damage since the amplitude of the low frequency cycles of the structural design loads increases. For a variable speed variable pitch wind turbine (Section 12), the pitch angle of the blades is controlled in response to a measurement of rotor speed. When the machine is subject to a change in windspeed, the pitch angle is only adjusted after the rotor speed has responded to the induced changes in the rotor torque. Because of the large rotor inertia the pitch regulation is slow and the wind turbine experiences large off design loads.

The control system also affects the structural fatigue by indirectly influencing the extent of part of the cyclic loads. Since all blades are assumed to act in unison, only those cyclic loads which enter the drive train and the cyclic loads which are correlated to them are affected. Usually, the most important of these cyclic loads are those which have frequency $n\Omega$ where n is the number of blades. They occur at too high a frequency to be directly controlled but at these frequencies the control system acts to enhance disturbances rather than to reduce them. Hence, the controller may increase substantially the cyclic loads of frequency n. For example, in respect to the tower shadow cyclic load on a two bladed wind turbine, the blades may be adjusted 180° out of phase to the response required to smooth the tower shadow cyclic load.

11 Constant speed wind turbines

A constant speed wind turbine is a simple configuration with the generator connected to the grid and directly driven by the drive train.

There is an extensive literature on the control of constant speed wind turbines with about 100 publications [12]. However, no treatment of the problem is entirely satisfactory. Frequently, there is no clear statement of the control objectives but the most common, often unstated, are

(*a*) power limiting
(*b*) power smoothing
(*c*) response to isolated gusts or ramps.

The treatment of the dynamics and the stochastic nature of the windspeed is also sometimes inadequate. The most thorough investigation to date is Mattsson [13].

The constant speed wind turbine configuration is characterised by stiff power train dynamics. The electrical generator is locked to the grid, thereby permitting only small deviations of the rotor shaft speed from the nominal value. The system is very responsive to wind induced load disturbances.

A typical wind turbine with appropriate rating for a given site spends about 25% of the time in each of the following modes [2]:

(i) shutdown as the windspeed is too low
(ii) generating below rated power
(iii) operating near rated windspeed, i.e. at the knee of the power curve
(iv) operating above rated windspeed.

When operating below rated windspeed no pitch regulation is normally undertaken. When operating above rated windspeed, one of the primary goals of the control system must be to minimise the stress on the power train since the power train and the gearbox in particular accounts for a significant part of the capital cost. It must also improve the power quality and not have any adverse effect on the structural loads.

For operation above rated windspeed the terms of the cost function in eqn. 22 which are important depends on the precise turbine configuration. When there is little compliance in the drive train there is no significant difference between the first five terms in eqn. 22 and a_1, a_3, a_4 and a_5 can be set to zero since the gearbox stress is the most important factor. The appropriate cost function is

$$J_1 = \int_{-\infty}^{\infty} \{a_2^2 S_{GB}(\omega) + a_6^2 |H_3|^2 S_C(\omega)\}\, d\omega \qquad (24)$$

Compliance and/or damping is sometimes added to the drive train at various points using mechanical devices such as quill shafts, torque limiting gearboxes and fluid couplings or generators with large amounts of slip. The added compliance protects the drive train components but this does not necessarily imply that the control action can be reduced since the first term in the cost function eqn. 22 may become significant. Hence, only a_3, a_4 and a_5 are now zero and the appropriate cost function is

$$J_2 = \int_{-\infty}^{\infty} \{a_1^2 |H_1|^2 S_E(\omega) + a_2^2 S_{GB}(\omega) + a_6^2 |H_3|^2 S_C(\omega)\}\, d\omega \qquad (25)$$

To illustrate the preceding consider the simplest configuration possible, i.e. a constant speed machine with no compliance adding devices in the drive train. The physical control model of the constant speed wind turbine in Reference 14 is depicted in Fig. 19 where

w = effective rotationally sampled windspeed
T'_f = aerodynamic rotor torque
T_f = rotor torque corrected for dynamic wake effects
P_e = electric power
P_{em} = measured electric power
v = measurement noise
P_{en} = nominal or rated electrical power
ϕ_d = demand pitch angle
ϕ_a = actual pitch angle

All the dynamic blocks are self-explanatory except the induction lag. When the windspeed or pitch angle changes it takes some time for the downstream wake of the wind turbine to adjust. The induction lag [5] is the dynamics associated with this aspect of the aerodynamics. The outputs the control system should be aiming to regulate are primarily T_s and for some configurations T_f. The variation of the aerodynamic gradients $\delta T_f/\delta w$ and $\delta T_f/\delta\phi_a$ over the operational domain of the wind turbine is quite strong and the control system must accommodate the range.

Four of the system outputs are very similar, namely the gearbox input torque, generator rotor speed, generator reaction torque and the power. In classical control terms there are only two independent cases. In the first case, the objective of the control system is to alleviate the transient component of the aerodynamic torque, Fig. 20, where T_s = gearbox input torque, T_{em} = measured torque, and T_o = nominal or rated torque.

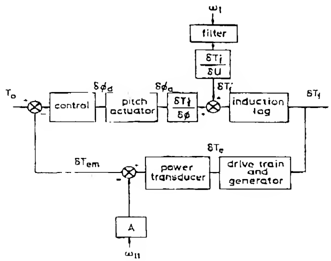

Fig. 20 *Control model with output of aerodynamic torque*

The second is to alleviate the transient component of the generator reaction torque, Fig. 21. The difference between the two interpretations is the role of the power train dynamics. In both, the windspeed turbulence ω_1 is treated as a disturbance which the controller is required to cause the system to reject. The hourly average windspeed changes are treated as a slow external disturbance which the controller regulates normally by integral action. For turbines with low slip generators the dynamics of the two cases may also be similar but the specification for the control systems can remain distinct.

The standard control action used in practice for wind turbines has been *PI* (proportional plus integral action). However, this may not be entirely satisfactory and it has been frequently shown that the addition of damping to

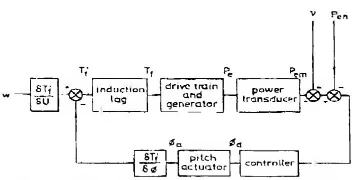

Fig. 19 *Physical control model for a constant speed wind turbine*

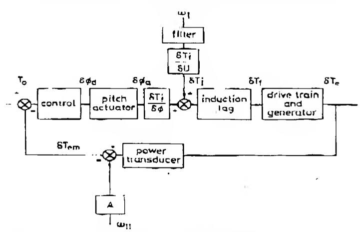

Fig. 21 *Control model with output of generator torque*

the system (by inclusion of feedback of slip measurement) improves performance [16, 17]. The reason is that the power train dynamics are characterisable as two modes. The first mode at low frequency is often near the bandwidth of the control system and is lightly damped to avoid the unnecessary dissipation of energy. Unfortunately, PI control is unable to add damping. Consider the control action

$$k_1 + \frac{k_2}{s} = k\left(\frac{s+a}{a}\right) \tag{26}$$

Fig. 22 shows part of the root locus for the dynamics of a typical wind turbine. The complex conjugate pair of poles are the first mode of the drive-train. When feedback is employed, k causes this pair of poles to track towards the imaginary axis and so reduces the degree of damping.

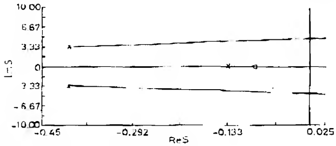

Fig. 22 *Part of root locus of open-loop system*

The Bode plot for $(s + a)/s$, Fig. 23 (for a nominally 10 rev/s) illustrates that it reduces the open-loop phase margin and so, also, must reduce damping. The obvious remedy of derivative action is not applicable because of the stochastic nature of the windspeed turbulence.

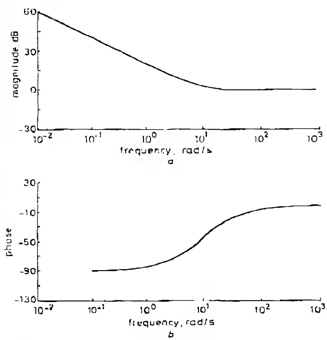

Fig. 23 *Bode Plot of $(s + a)/s$ with $a = 10$ rev/s*
PI compensator $k = (s + 10/s)$

One further goal the control system should attempt to realise is to maximise the energy capture of the wind turbine, particularly when operating near to the rated windspeed. The aims of the control system [1] are summarised as follows:

(*a*) Alleviate transient loads throughout the wind turbine to relieve stress.

(*b*) Regulate and smooth the power generated.

(*c*) Shape the dynamics to satisfy the usual performance criterion, i.e. impart satisfactory stability margins and steady state errors.

(*d*) Maximise energy capture.

12 Variable speed wind turbines

In variable speed wind turbines the generator does not directly couple the grid to the drive train. Instead the rotor is permitted to rotate at any speed by the power generation unit which might typically be a generator-rectifier-inverter combination.

The ability to operate at varying rotor speed, effectively adds compliance to the power train dynamics of the wind turbine. Hence, although all the aspects investigated in Sections 7 and 8 are still relevant, the weighting given to the goals of alleviating stress on the power train need not be so great. However, it must still be evaluated. As the shaft speed varies the frequency of the peaks of $S_u(\omega)$ vary as does the frequency of the structural modes, although the extent of the variation for the latter is relatively small [2, 5]. It may be assumed the rate of change of the mean rotor speed is slow compared to the rapid fluctuations in the windspeed and loads. The variable speed wind turbine can, thus, be analysed quasistatically in the manner of the constant speed wind turbine Because of this movement in the spectral peaks the requirement on the structural dynamic loads may be more stringent.

For the variable speed wind turbine there may be more than one control action. When the power generation is by an AC-DC-AC link there are three, namely

(i) an AVR (automatic voltage regulator) on the generator output voltage

(ii) control of the power electronics links to the grid

(iii) variable blade pitch.

In addition to power measurement, a measurement of shaft speed may also be made. Used in conjunction (i) and (ii) control the electrical power generated and therefore the generator reaction torque which obviously influences the rotor speed Control without pitch action through the generator reaction torque can be analysed in a similar manner to pitch regulation, but without the shaping of the windspeed spectral density function by $|1 + CP|^{-2}$. Whether satisfactory control can be attained in this manner alone, e.g. by stalling the rotor above rated windspeed, needs to be investigated. Alternatively active pitch control is used in conjunction with generator reaction torque. In the latter case the design of the control system is a genuine two input two output control problem with significant interaction between the two control actions [18].

There are a variety of different operating strategies for variable speed wind turbines and each could be evaluated separately. The turbine is caused to track a predefined torque-speed trajectory and an additional goal of the control system is to track this trajectory as closely as possible [19]. A typical strategy is described below.

Below rated wind speed the operation of the turbine is regulated by varying the generator winding voltage or the inverter firing angle. In essence the load on the generator is adjusted and so is the reaction torque the gener-

ator imparts to the drive train. This facility is used to vary the rotor speed. The aim is to cause the wind turbine to extract energy from the wind as efficiently as possible. As a given windspeed the efficiency peaks at a specific rotor speed. In Fig. 24 [20], the relationship between the torque on the rotor induced by the wind and rotor speed is depicted by curves each of which is for a constant wind speed. The locus of states of maximum efficiency is the curve C_{pmax}. To maximise energy capture below rated windspeed the wind turbine is controlled to track the curve *ab* from left to right as the windspeed rises.

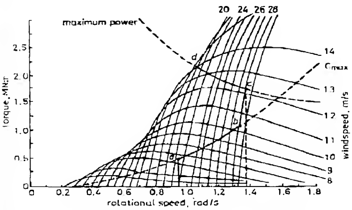

Fig. 24 *Torque/speed curves for a variable speed wind turbine*

Above rated windspeed there is a large range of modes of operation [20]. One approach is to control the turbine to track the curve *cd* on Fig. 24 from right to left as the windspeed rises. The motivation is that as the rotor speed falls the rotor stalls which reduces the loads on the blades and makes the loads less sensitive to variations in windspeed. Another approach is to combine variable speed operation with a variable pitch capability. There are now two control actions, the generator reaction torque and blade pitch angle.

The control problem for the variable speed wind turbine has a number of additional features compared to the constant speed machine. The dynamics of the variable speed generator are more complex and highly nonlinear. The constant speed generator is enclosed by a very strong feedback loop from the direct attachment to the grid. In consequence the dynamics of the generator are simplified and essentially linear. The variable speed generator is open loop unstable. When the wind induced torque increases the rotor accelerates but the generator reaction torque decreases with the resulting increase in shaft speed. The wide range of rotor speeds inevitably implies that the turbine encounters structural resonances.

The appropriate cost function is shown in eqn. 23 with all terms included. There is an extensive range of possible configurations with various choices of range of speed, power generation unit and control actions. The weightings in eqn. 23 are chosen accordingly. Very little attention has been paid to the control problem and there are only about 10 publications [12] on the subject. The general objectives are the same as for constant speed wind turbines but in addition the variable speed wind turbine must be regulated to exploit it to the full the variable speed facility by tracking some curve in the torque/rotor speed plane. Of course, improvement in tracking must not be at the expense of reducing the power factor.

13 Measurements for control

The electric power generated is the most basic and simple measurement that can be made of the wind turbine state. It is sometimes suggested [16] that it might be advantageous to supplement power measurement with direct slip measurement, particularly for the constant speed wind turbines, since the delay due to the generator time constant is removed from the measurement dynamics. However this argument is not justified [1]. The generator exerts a strong torque feedback which effectively couples together the slip and reaction torque of the generator. Because the power and reaction torque are also strongly coupled, slip and power measurements are equally valid from a control viewpoint. In studies [17], where a feedback based on slip measurement is included in the control system, the results are frequently improved but this is because the slip measurement is being used to add damping to the system and not because the slip measurement is inherently better. Damping can readily be added to the control action by other means.

Other measurements on the drive train are possible such as shaft speed or shaft torque. Provided information over the frequency range required by the controls system can pass down the drive train, measurements of torque in addition to power are unnecessary. For variable speed wind turbines a measurement of speed shaft is required since the control system tracks a torque-speed trajectory. Shaft speed is differentiated from slip. The former is the absolute rotational velocity whereas the latter is the difference between the shaft speed and the rated shaft speed. The measurement of slip requires a far higher degree of accuracy.

No individual monitoring of the rotor blades is required since they are assumed here to act in unison.

The final measurement which might be of interest is windspeed. A measure of the mean windspeed is of course useful for general operation of the turbine but it is problematic to obtain a representative windspeed as experienced by the turbine [1]. The best anemometer for the wind turbine is the turbine itself.

14 Implications of control for wind turbine design

Mechanical damping is often added to the drive-train of wind turbines. The control system is an alternative means of adding damping which avoids the dissipation of power as heat within the power train. It might even be used in this manner below the rated windspeed.

Each specific wind turbine configuration has a characteristic frequency (related to the dynamics of the blades and their actuating systems and the torsional stress the blades can sustain) above which the control system cannot operate. For lower frequencies the control system should regulate the loads and for higher frequencies the compliance of the power train should absorb the loads. There should not be a significant gap between the maximum frequency at which the control system can operate and the minimum frequency at which the compliance of the drive train becomes effective. If a significant gap exists, the wind turbine will be subject to unregulated loads.

The control system requires information on the loads it is required to counteract. Therefore, information at all frequencies up to the characteristic frequency of the controls system must be passed to the measurement transducer. To avoid the need for high gain controllers with

their associated noise problems, no component of the power train should act as a low-pass filter in the frequency range of the control system, i.e. the bandwidth for each component must be greater than the characteristic frequency. Consider the power train, Fig. 25. None of the components should prevent information from passing down the power train to the output measurement. If a component does, relevant information becomes unavailable to the control system which is rendered ineffective for part of its frequency range. An additional measurement before the restriction is necessary to recover the lost information.

consideration. Stall regulation is still at the development stage and will not immediately supersede pitch regulation, particularly for large machines.

Power quality, alone, is too blunt a criterion on which to assess the design of the controller for variable pitch regulation. There is an extensive range of strategies which can be adopted without significant loss of power quality. The dynamics of the controller interact with the dynamics of the structure and so have implications for the fatigue life of the turbine. Similarly, the dynamics of the controller interact with the dynamics of the drive train and have implications for the fatigue life of the drive train components The choice of control strategy moderates or accentuates the torques and moments to which the components of the wind turbine are subject. If the torques and moments are moderated then, of course, the power quality improves, but to improve the power quality alone will not by itself moderate the torques and moments. Good control must aim to moderate them.

The relative importance of each of the factors involved in the assessment of the control design is strongly dependent on the turbine configuration and inevitably will involve tradeoffs. For variable speed machines some requirements can be relaxed because of the increased compliance in the drive train as compared to the constant speed case. But others become more stringent since the shaft speed varies and the turbine is caused to track a predefined torque-speed trajectory.

To date wind turbine control has been judged in terms of power quality or in terms of the response of the wind turbine to simple wind profiles such as an isolated gust or ramp in windspeed. These are not adequate criteria on their own. 'Good control' should aim to realise the following objectives:

(*a*) Relieve stress and reduce fatigue on the wind turbine by smoothing the torques and moments throughout the systems.

(*b*) Maximise energy capture of the wind turbine.

(*c*) Regulate and smooth the power generated.

(*d*) Shape the dynamics of the complete power train to the usual performance criterion, i.e. impart satisfactory damping and steady state behaviour.

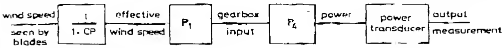

Fig. 25 *Flow of information along wind turbine power train*

15 Implications of control for cost of power generation

The control system has implications for the cost of power generation by wind turbines since it reduces the load fluctuations and stress to which the machine is subject. The specification of components can be set closer to the nominal rating. The control system can also improve the rate of energy capture. Both of these factors are related to the cost of power generation. Only a thorough investigation of the control design problem can clarify the tradeoff decisions contributing to a minimum cost, long life system.

16 Summary and conclusions

Variable pitch control on wind turbines was introduced for the following reasons. Turbines must be capable of being started and run up to speed in a safe and controlled manner; stopping must be similarly controlled. In emergency conditions overspeed protection must be provided and industrial practice has tended not to favour a reliance solely on mechanical brakes. The general opinion is that some aerodynamic assistance is preferred for these operations. The power of the wind increases sharply with windspeed. At a predetermined windspeed the power input to the turbine will have reached the limit for safe operation. To prevent overload as the windspeed rises above rated, the turbine must be regulated to spill the excess power in the wind.

Rapid windspeed changes produce variation in loads which cannot be completely eliminated. Reducing the magnitude of these variations is desirable as it allows the turbine to be operated closer to its design limits without fear of electrical or stress overloads; an increase in power production or a reduction of component ratings are thus possible. 'Smooth' output power also has a traditional appeal to the electricity supply industry as it has no experience of such rapidly fluctuating power sources. The more refined commercial turbines strive to obtain 'good power quality'.

Improvement in power quality can be achieved by using a control system which monitors the turbine and alters the pitch angle of the blades accordingly. An alternative is to design a fixed pitch rotor with blades that stall at the rated windspeed. A stalling rotor is self-regulating providing power regulation and good power quality without a control system. Start up, shut down and overspeed protection of such a rotor, requires further

Active pitch control modifies the spectral density function of the windspeed the wind turbine effectively experiences. This effective spectral density function generates the fluctuating loads to which the wind turbine is subject. One approach to wind turbine design is to overengineer the system to the extent that the structural and power train dynamics decouple and the components are specified to be capable of absorbing all the fluctuating loads. An alternative is to reduce the over-engineering to a minimum by regulating the response of the wind turbine to the fluctuating loads The historic trend is to the latter as turbines become lighter, more flexible and hence more cost effective [21]. To investigate and assess any aspect of performance of such wind turbines requires the dynamics to be subject to the correct input. That requires the shaping by the action of the controller to be incorporated and is dependent on the quality of the control. Likewise, that the action of the control system shapes the input in

this manner, must be recognised when designing the control system. The most direct and secure route to the lowest cost turbine is through a consideration of the complete system and its environment including the control system [22].

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